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Measure of a flow electrification potential profile with the Capacitive Traveling Method

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Abstract- In a solid/liquid interface, different physicochemical reactions lead to a charge transference that produce a charge distribution known as electrical double layer (EDL). For the dielectric pipelines, with a constant inlet flow, the positive charge in the liquid is described by the Stern model in two zones: compact layer and diffuse layer. Whereas, the negative charge in the solid is described electrically as an arrange of resistance and current generators. The EDL has been studied at the Pprime Institute with a close-loop hydraulic circuit that allows the control over the flow conditions. By the electrical isolation of a pipeline segment it has been possible to study different parameters of the EDL in function of the liquid, however the behavior of the local charge accumulation in the solid remains unknown. In order to analyze the solid behavior, a method called “capacitive traveling method” was developed. It consists of a capacitive arrange placed in front of the charged surface. As the sensor moves, a mirror charge is induced in function of the potential over the surface and a current is generated. By the system modeling, it is possible to convert the sensor output into the potential profile due to the charge accumulation over the surface which is the objective of this work.

I. INTRODUCTION

The charge polarization, due to the electrical double layer (EDL), at the solid/liquid interface is a phenomenon that has been studied for many years [1-6]. In electrical apparatuses, such as transformers, this behavior can be the origin of different problems as: material degradation, electric arcs or even explosions in the worst scenario. For this reason, the Pprime institute developed, 20 years ago, a close-loop hydraulic circuit which simulates the conditions at the mineral oil/pressboard interface (commonly used in transformers). This device allows to determine the overall electrical equilibrium of the accumulated charge at the interface, but the local evolution of the potential along the pressboard remains unknown.

In order to evaluate the potential distribution over the pressboard layer, the capacitive traveling method was developed. This technique consists of a capacitive arrange that is placed in front of the specimen surface. When the sensor moves, a mirror charge is induced in function of the potential change over the surface and an electrical current is generated. Through the mathematical modeling of the system, the original potential profile can be calculated from the sensor output.

The objective of this work is to present a new technique to measure the local potential distribution of a dielectric surface based on the capacitive traveling method. This first attempt corresponds to a fundamental study of the charge distribution in solid/liquid interfaces.

II. Theory

At the liquid/solid interface, different physicochemical reactions appear and lead to the creation of the electrical double layer (EDL). According to the Stern’s model [4], the EDL is composed of two zones of opposite signs (one inside the solid and one another in the liquid). In the liquid two different regions appear: the compact layer and the diffuse layer. The compact layer, of some angstroms of thickness, is next to the solid part and is considered as static. Whereas, the diffuse layer, of a larger thickness, is assimilated to the Debye length. The charges in the diffuse layer, represented by the space charge density (ρ), can be transported by the liquid flow. According to the Boltzmann’s law, as the distance to the solid wall increases, the charge density decreases. For a mineral oil/pressboard interface (figure 1), the classical distribution of the charge is negative for the solid and positive for the liquid.

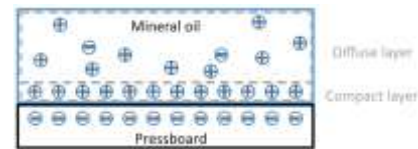


Fig. 1. Model of the EDL at the Pressboard/mineral oil interface.

The flow electrification process starts when an inlet flow appears at the solid/liquid interface. At this moment, the charges on the diffuse layer (liquid) start to move by convection and new charges are created at the interface to reach a new equilibrium. At the duct inlet, where the liquid is fresh and no EDL is created, the EDL disequilibrium at the interface is maximal as well as the charge generation. On the other hand, at the duct outlet, a new dynamic equilibrium is reached and the charge generation is minimal. If the solid is a dielectric surface, a charge accumulation will be produced. In order to modeling the electrical behavior of the charge transference at the mineral oil/Pressboard duct, a circuitual modeling was proposed by Paillat et al [6] (figure 2).

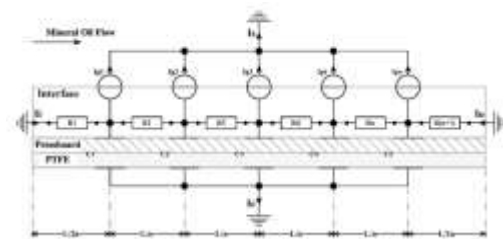


Fig. 2. Electrical model for a dielectric surface.

In the electrical model, the charge separation that has placed on the solid surface during the flow electrification process can be associated with an arrange of current generators. At the duct inlet, the generators magnitude is maximal and its value decrease along the surface. Whereas, the π arrangement of the capacitors and resistances represents the total surface of the solid. The model components are supposed to be constant, however the EDL change the local conductivity of the liquid. As a result, the resistances near to the solid edges (assumed by Paillat as grounded terminals) are weaker and the charge can easily leak on these regions. The electrical model of this phenomenon allows to simulate the distribution of the negative potential profile at the interface. The figure 3 shows an example of the dimensionless potential in function of the x-direction.

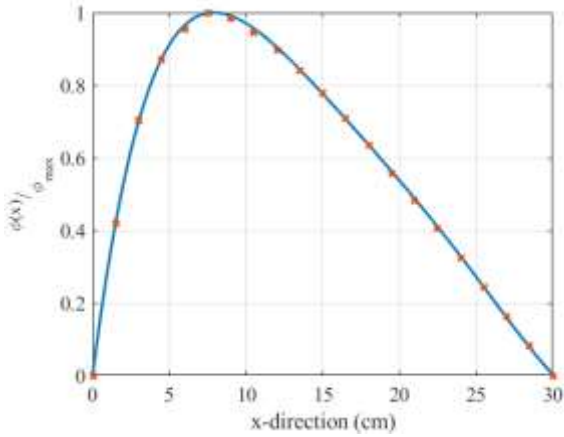


Fig. 3. Simulated potential profile distribution over a dielectric surface versus the dimensionless length of the duct.

The simulated potential profile over the pressboard layer, shown in the figure 3, starts and finish at zero by the grounding condition imposed by Paillat at the edges of the surface. Along the surface, the negative distribution of the potential (shown as an absolute value) passes for a maximal value. The position of this maximal potential seems to be close to the duct inlet. The potential distribution at the interface is, typically, a compromise between the generated electrical charges and the charges leaks to the ground along the duct.

III. Description of the experimental setup

The experimental setup consists of a closed hydraulic loop of mineral oil flowing through the measurement cell (figure 4). This arrange is composed of a 30 cm-long rectangular Pressboard channel inserted in a PTFE frame. On each side of the channel, a grounded electrode is employed to fix the potential at 0 V (same conditions imposed on the equivalent electric model). At the outer side of the channel, the traveling electrode is placed (Figure 5). This electrode allows the measuring of a current response (i_t) induces by the potential variation at the interface during its displacement. Due to the mechanical disposition of the sensor, the current measurement starts at 5.5 cm of the dielectric surface origin and covers 10 cm of its surface.

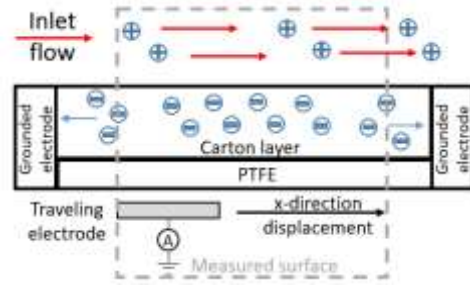


Fig. 4. Measurement cell.

The traveling sensor consists of a measuring electrode of 5x35 mm surrounded by a guard ring. To prevent the capacitance coupling, produced by lateral unexpected displacements, the sensor is Underlapping-Underlapping type [7]. In addition, the guard electrode limits the fringing effect. All the electrodes used have rounded corners to prevent the deformation of the electric field. The sensor arrange is connected to the pico-ammeter Keithley 610C.

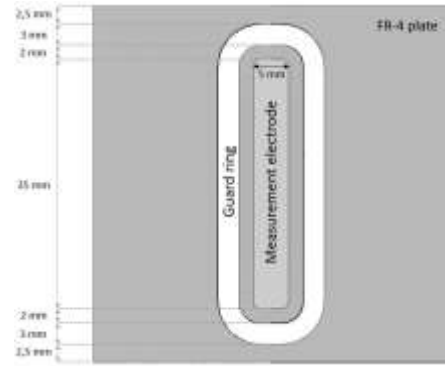


Fig. 5. Traveling electrode.

III. Measurement principle

A. Measured potential profile

As soon as the sensor is placed in front of the measured surface, a parallel plate capacitor appears (C_m , figure 6). The effective surface of this capacitor (l_{eff}) is the sum of the sensor surface (I) and the measurement cone (II), as described in the equation 1. The potential profile recovered by the moving sensor (p_m) corresponds to the mean value of the potential over the surface (ϕ) inside the sensor effective surface (equation 2).

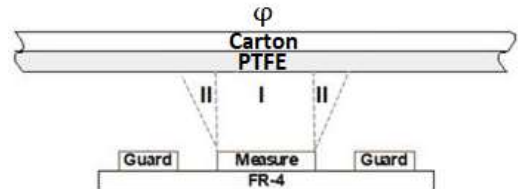


Fig. 6. Effective surface of the sensor.

$$l_{eff} = l_{elec} + 2l_{cone} \quad (1)$$

$$p_m = \frac{1}{l_{eff}} \int_x^{x+l_{eff}} \phi(x) dx \quad (2)$$

This technique was calibrated by the potential measurement and reconstruction of an imposed single-step potential profile (not included in this paper) [12]. At first, a close relation between the parallelization of the sensor and the system response was found. If the sensor is not correctly parallelized, an additional capacitance variation can be induced into the system and a current can be generated. Also, a calibration process was realized in function of the distance to the measured surface. For a gap of 2.5 mm, the error in the reconstructed potential remains inferior to 10%. However, this value increase with the distance.

B. Electrical model of the sensor

In order to find a relation between the measured potential profile and the sensor output, an electrical equivalent model of the sensor was developed (figure 7). This model takes into account the equivalent capacitance between the sensor and the surface (c_m), the leaks in the connecting cables (c_c), and the equivalent circuit of the pico-ammeter where r_a is the measurement resistance and c_a the capacitive leaks. The relation between the measured current (i_m) and the mean potential (p_m) is shown in the equation 3. For this model it was taken into account the variation of the sensor capacitance (c_m) over the surface. Finally, to recover the potential variation profile from the measured current, the equation 3 was discretized and the Runge-Kutta numerical method of 4 order was implemented. This system is characterized for a response time of 1.25 s and a sensibility of 0.1 pA/V for an electrode of 5x35mm at a 2.5 mm of the surface with a displacement speed of 1 mm/s. The distribution of the potential on the surface is determined at the integration constant (p_i) which can only be determined experimentally.

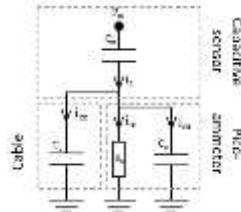


Fig. 7. Electrical modeling of the sensor.

$$\frac{dp_m}{dx} = \frac{i_m}{c_m v} \left(1 + r_a v \frac{dc_m}{dx} \right) + \frac{r_a i_m}{c_m c_m v} (c_m + c_c + c_a) - p_m v \frac{dc_m}{dx} \quad (3)$$

IV. Results and discussion

A. Capacitance over the dielectric

To calculate the potential profile from the measured current, it is necessary to calibrate the capacitance variation of the sensor over the surface. To do this, a multipoint test was realized every 1 cm starting from 5.5 cm of the duct inlet. For each point, the value of the capacitance (C_m) was found by dephasing current estimations (figure 8). The capacitance profile shows a constant decrease with a slope of $-2.6 \cdot 10^{-13}$ F/m. This variation can be attributed to a small change on the PTFE

thickness or to a constant air-gap change between the sensor and the surface.

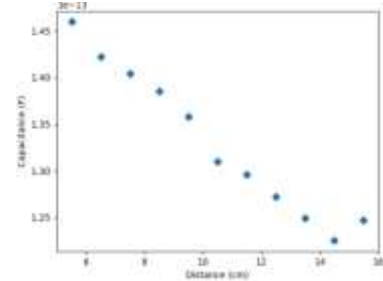


Fig. 8. Capacitance over the dielectric surface.

B. Measured current profile

The measurement of the current profile was realized in two steps (figure 9). At first, a reference current profile was taken at the dielectric surface without inlet flow. Secondly, an inlet flow of 0.7 m.s^{-1} of mineral oil was added to the interface. In order to have the same test conditions, a time of 30 minutes was imposed between measurements. Besides, the test under the inlet flow conditions were made after 120 minutes to ensure the chemical equilibrium of the system. The current profiles with and without inlet flow seems to have the same spatial behavior but different amplitude. This behavior can be influenced by the potential distribution over the PTFE interface. Under the charge superposition principle, the difference between the current profiles (with and without inlet flow) correspond to the current profile on the dielectric surface produced by the EDL (figure 10). Each curve represents the mean value between six measurements with a standard deviation lower than 5%.

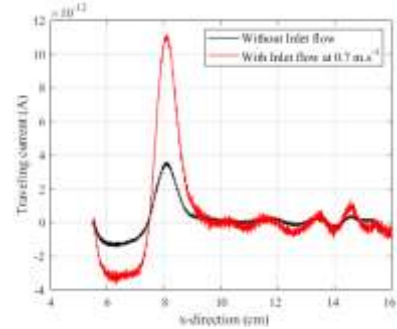


Fig. 9. Measured current profiles with and without inlet flow.

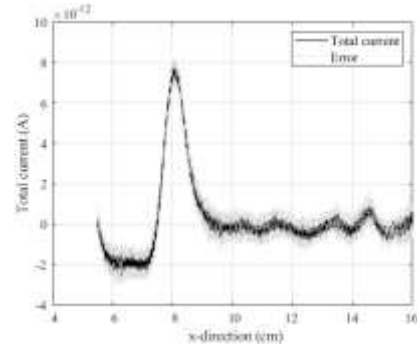


Fig. 10. Current profile produced by the EDL.

The measured current produced by the charge convection in the mineral oil is positive (not presented in this paper). So, by the EDL principle, the current on the Pressboard is taken as negative as well as its associated potential distribution. The current profile produced by the EDL of some pico-amperes (total current) is negative at the duct inlet. It passes by a minimum value and then increases at a lower rate. Then, it becomes positive. The current passes by a maximal point and then decreases at a high rate. Finally, at 10 cm of the surface, the measured current is almost zero.

C. Calculated potential profile

The potential profile calculated from the current measurements is shown in the figure 11. It represents the potential variation over the dielectric surface from $x = 5.5$ cm to 15.5 cm. The negative potential variation is determined at the integration constant (π) which can only be determined experimentally. The potential profile can be divided into three zones:

- 5.5 – 7.5 cm: The negative potential increase at a constant rate. In this zone, the negative charges are trapped on the Pressboard with a maximum charge accumulation at 7.5 cm. Based on the simulated potential (figure 3), it is possible to assume that the potential increases negatively in this region. This behavior indicates the presence of an increase quantity of trapped charges.
- 7.5 – 9 cm: The negative potential decrease and reach a minimal value. In this region, the electrical double layer is more developed, and the chemical imbalance becomes lower. So, there is a decrease in the electric charge created and trapped within the Pressboard.
- 9 – 15 cm: The potential seems to be constant. This behavior is consistent with the simulated potential profile (figure 3). However, a small increase is observed, probably, as a result of the low measured current (figure 10) which is close to 0 A.

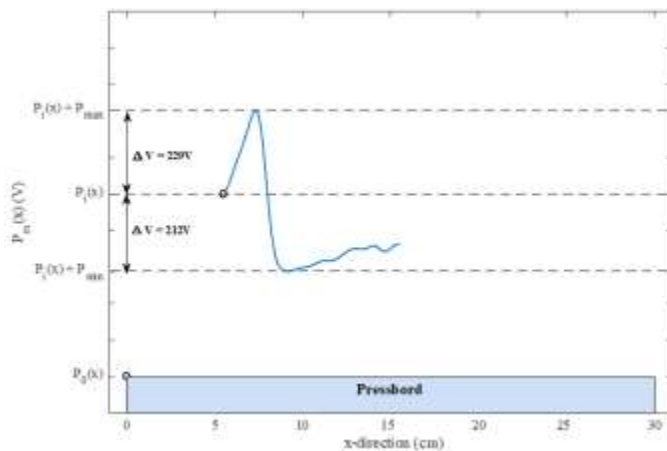


Fig. 11. Potential variation over the surface.

The potential variation profile found by the capacitive traveling method seems to be in accordance with the simulated

potential profile over a dielectric surface (figure 3). For both profiles, the potential pic seems to be at the beginning of the interface.

V. Conclusions

The present paper investigates the use of a new technique called “Capacitive Traveling Method” to realize a non-intrusive measurement over a dielectric surface. Using a mineral oil with an inlet flow of 0.7 m.s^{-1} it was possible to measure the charge at the solid/liquid interface (current profile) as well as his potential variation. It was found that the general behavior of the calculated potential profile at the interface, specially the pic founded at the duct inlet, seems to correspond to the theoretical approaches.

ACKNOWLEDGMENT

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